Roles of Plasmoid Instability in Magnetic Reconnection and Magnetohydrodynamic Turbulence

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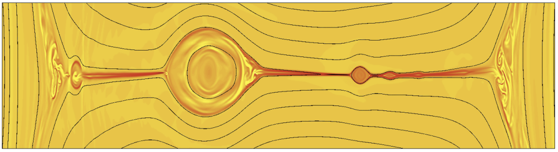
Outline of Today's Talk

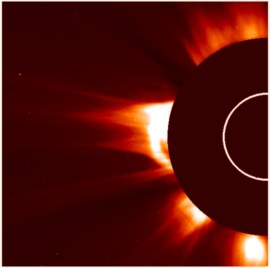
- Plasmoid instability in evolving current sheet and current sheet disruption
    - Results from direct numerical simulations
        - Scalings of the current sheet width, linear growth rate, and dominant wavenumber at disruption
    - A phenomenological model and analytic scalings in the high-S regime
- Plasmoid-mediated current sheet disruption & MHD turbulence
- Evidence of plasmoid instability in solar observation
- Future perspectives

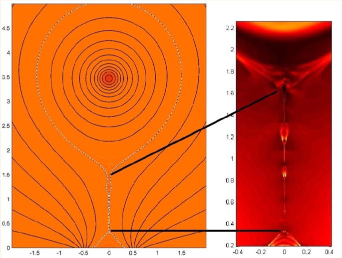
Plasmoid Instability Brings New Perspectives to Reconnection



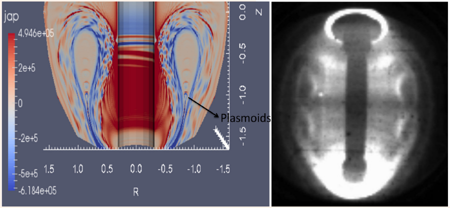
- The reconnection current sheet is unstable to secondary tearing instability at high S, leading to current sheet fragmentation and formation of plasmoids
- Reconnection is fast even in resistive MHD, with reconnection rate $\sim 0.01 V_A B$, nearly independent of S. (Bhattacharjee et al. 2009; Cassak et al. 2009; Huang & Bhattacharjee 2010)
- Even faster collisionless/Hall reconnection can be triggered if the secondary current sheets become small than ion skin depth d_i or Lamor radius ρ_i. (Daughton et al. 2009, Shepherd & Cassak 2010, Huang et al. 2011)

Plasmoids in Nature and Laboratories

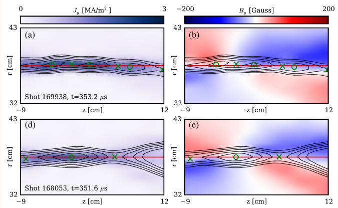




Guo et al. APJL (2013)



Ebrahimi & Raman 2015, 2016



Jara-Almonte et al. PRL 2016

Plasmoid Instability in Evolving Current Sheet

- The linear growth rate in a Sweet-Parker current sheet $\gamma_{max}\tau_A \sim S^{1/4}$, which diverges as $S \to \infty$.
- Because a Sweet-Parker sheet must be realized dynamically over time, the current sheet will break apart before it reaches the Sweet-Parker width for a high-S system. (Pucci & Velli 2014)
- **Plasmoid instability & current sheet disruption must be studied in the context of an evolving current sheet.**
  - Tenerani et al. (2015), Uzdensky & Loureiro (2016), Comisso et al. (2016, 2017), Huang et al. (2017), etc.
- **Key Questions** — When will the current sheet be disrupted? How do current sheet width, growth rate, dominant wavenumber at disruption scale with S *and other parameters?*

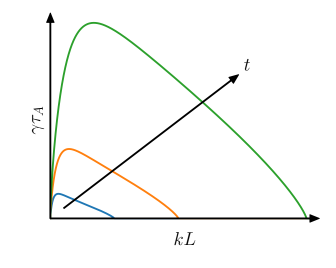
Tearing Instability in Thinning Current Sheet

Harris sheet profile $\mathbf{B} = B_o \tanh(x/a)\hat{\boldsymbol{y}}$

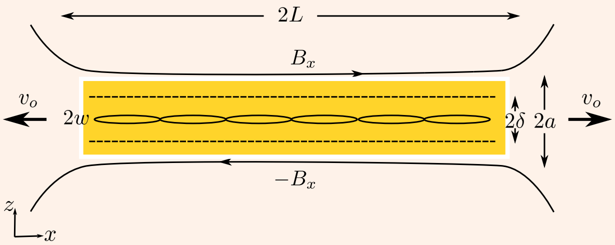
$$\gamma\tau_a \sim \begin{cases} S_a^{-3/5}(ka)^{-2/5}(1-k^2a^2)^{4/5}, & ka \gg S_a^{-1/4} \\ S_a^{-1/3}(ka)^{2/3}, & ka \ll S_a^{-1/4} \end{cases}$$

Coppi et al. 1976

- Here the Lundquist number $S_a = aV_A/\eta$ and the Alfvén time scale $\tau_a = a/V_A$ are defined with the current sheet **thickness** a.
- As $a(t)$ decreases in time, the growth rate γ increases and more modes become unstable.



Condition For Disruption



- Inner layer half-width

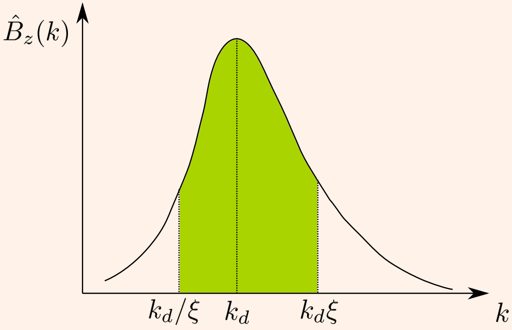
$$\delta = \left(\frac{\gamma}{V_A/a} \frac{1}{(ka)^2 S_a} \right)^{1/4} a$$

- Island half-width

$$w = 2\sqrt{\frac{a\tilde{B}}{kB_x}}.$$

- Tearing instability becomes nonlinear when $w = \delta$. At this time $\tilde{J} \sim J$ and the current sheet is "disrupted".

Estimating Island Size with Superposition of Modes

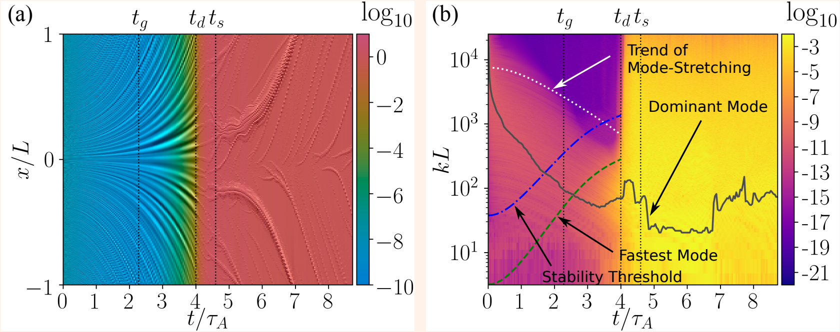


$$\tilde{B} = \left(\frac{1}{\pi L} \int_{k_d/\xi}^{k_d\xi} |\hat{B}_z(k')|^2 dk' \right)^{1/2}$$

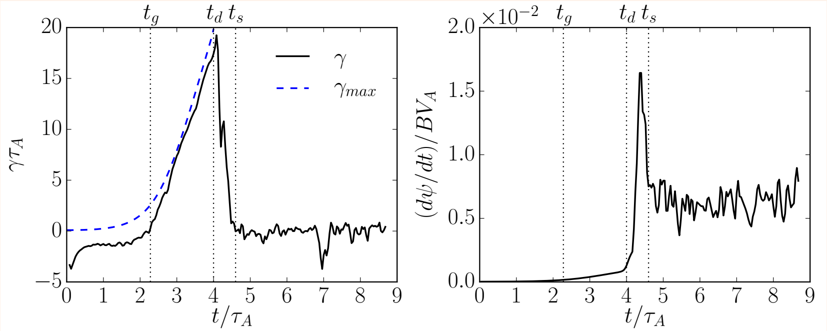
$$w = 2\sqrt{\frac{a\tilde{B}}{k_d B_x}}.$$

Evolution of Fluctuations, $S = 2.5e6$

Real Space   Fourier Space

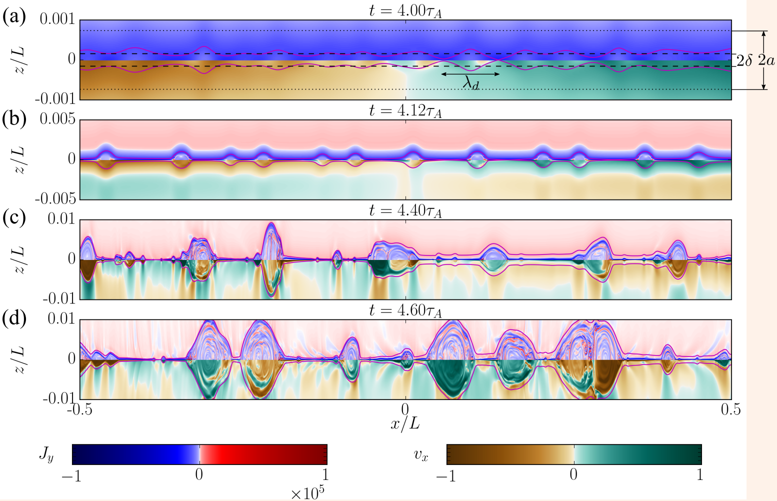


- Fluctuations are stretched along the x direction by the outflow jets: $dk/dt = -kv'_x$
- t_g: amplitude starts to grow; t_d: disruption; t_s: saturation

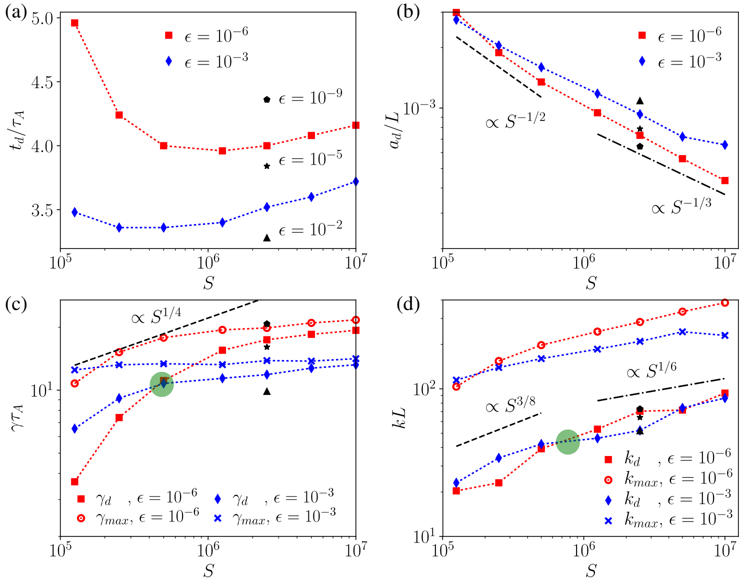


- The "total" perturbation amplitude $||\tilde{B}_z|| \equiv \left(\int_{-L}^{L} \tilde{B}_z^2 dx\right)^{1/2}$ typically starts to grow when $\gamma\tau_A \simeq O(1)$, and $\gamma\tau_A \gg 1$ at the disruption
- Onset of fast reconnection at $t = t_d$

Snapshots from Disruption to Saturation



Scalings from Simulations



A Phenomenological Model

- Mode-stretching by outflow jets

$$\frac{dk}{dt} = -kv'_x$$

- Evolution of the fluctuation spectrum $f(k) \equiv |\hat{B}_z(k)|/B_0 L_0$

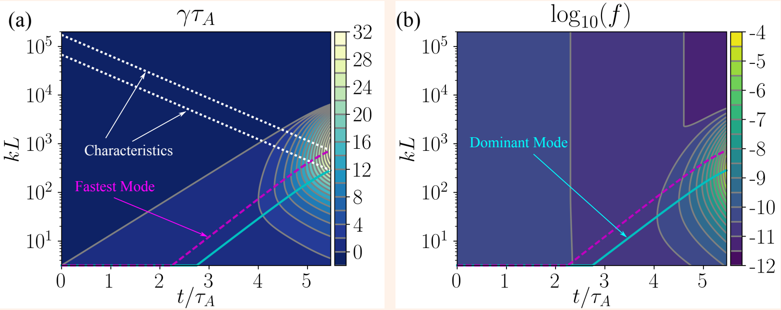
$$\frac{df}{dt} = \partial_t f - \underbrace{kv'_x \partial_k f}_{\text{Stretching}} = \Big(\underbrace{\gamma(k, a(t))}_{\text{Linear Growth}} - \underbrace{\frac{v'_x}{2}}_{\text{Advection Loss}} + \underbrace{\frac{1}{2L}\frac{dL}{dt}}_{\text{Length Evol.}} \Big) f.$$

- Only consider the domain $k \geq \pi/L$.
- Disruption takes place when island size = inner layer width of the dominant mode

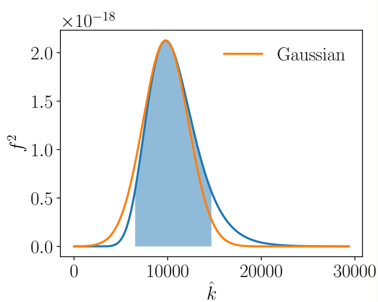
Solving the Model Eq. by Method of Characteristics

Assuming $dL/dt = 0$ and $v_x' = V_A/L$, along a characteristic $\hat{k} = \hat{k}_0 e^{-(\hat{t}-\hat{t}_0)}$,

$$f(\hat{k},\hat{t}) = f(\hat{k}_0,\hat{t}_0)\exp\left[\underbrace{\int_{\hat{t}_0}^{\hat{t}} \hat{\gamma}\left(\hat{k}(\hat{t}'),\hat{t}'\right)d\hat{t}'}_{\text{can be expressed in } {}_2F_1} - \frac{\hat{t}-\hat{t}_0}{2}\right].$$



Condition for Disruption



$$\hat{\delta} = \hat{w} \Longrightarrow \left(\frac{\hat{\gamma}_d}{(\hat{k}_d \hat{a}_d)^2 S} \right)^{1/4} \hat{a}_d = 2\sqrt{\frac{\hat{a}_d \tilde{B}}{\hat{k}_d B_0}}$$

$$\tilde{B}^2 = \frac{B_0^2}{\pi} \int_{\hat{k}_d/\xi}^{\hat{k}_d \xi} f^2 d\hat{k} \simeq \text{Gaussian Integral}$$

Analytic Scalings of Disruption Conditions

For $\hat{a} = \hat{a}_0 e^{-\hat{t}/\hat{\tau}}$, $f_0(\hat{k}_0) = \epsilon \hat{k}^{-\chi}$, the disruption width

$$\begin{aligned}\hat{a}_d =& c_a \hat{\tau}_\sharp^{2/3} S^{-1/3} \left[-\frac{1}{\theta} W_{-1}\left(\Xi\right) \right]^{-2/3} \\ \simeq& c_a \hat{\tau}_\sharp^{2/3} S^{-1/3} \left[\log\left(\epsilon^{-2} \hat{a}_0^{(2\chi+1)\hat{\tau}} \hat{\tau}_\sharp^{1/2-1/\theta} S^{(1/\theta-\chi-3)/2} \right) \right]^{-2/3},\end{aligned}$$

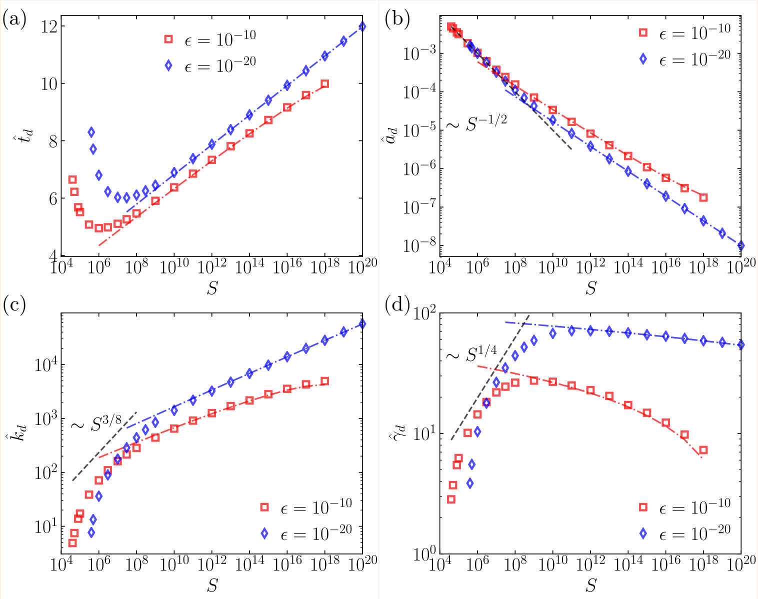
where W_{-1} is the Lambert's W function, $\hat{\tau}_\sharp \equiv 5\hat{\tau}/(\hat{\tau}+5)$,

$$\Xi \equiv -\theta c_a^{3/2} \left(c_\chi \epsilon^{-2} \hat{a}_0^{(2\chi+1)\hat{\tau}} \right)^{-\theta} \hat{\tau}_\sharp^{1-\theta/2} S^{(\theta\chi+3\theta-1)/2},$$

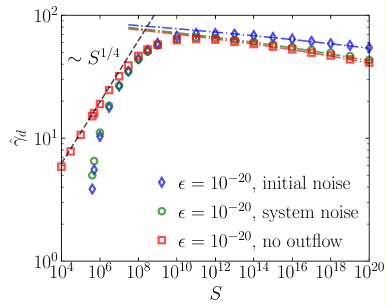
$$\theta \equiv \frac{3}{(4\chi+2)\,\hat{\tau} + 5\chi + 2}.$$

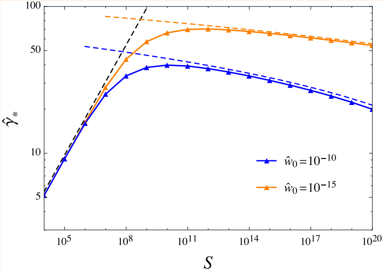
Dominant wave number $\hat{k}_d = c_k S^{-1/4} \hat{a}_d^{-4/5}$, growth rate $\hat{\gamma}_d = c_\gamma S^{-1/2} \hat{a}_d^{-3/2}$.

Scalings from the Phenomenological Model



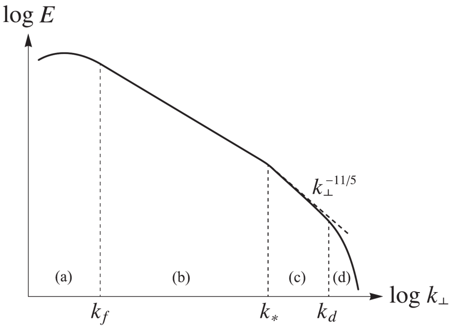
The Effect of v'_x Is More Significant In The Low-S Limit





- Calculations can be done with a system noise instead of an initial noise, or without the effects of v'_x.
- if $v'_x \to 0$, with a proper translation of notations $f_0(\hat{k})\hat{k}^{-1/2} \leftrightarrow \hat{w}_0(\hat{k})^2/4\hat{a}_0$, the analytical scalings from the model are identical to that of Comisso et al. (2016, 2017) up to the leading order logarithmic expansion.

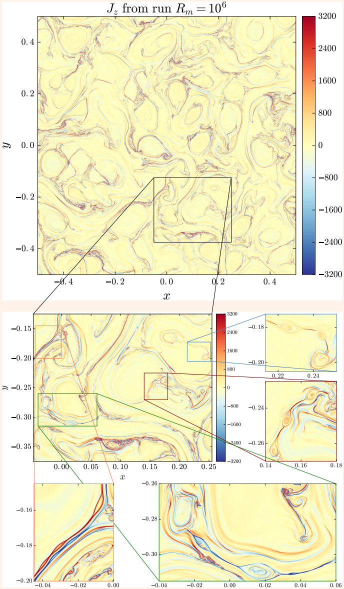
Application: Plasmoid-Mediated Reconnection in Turbulence

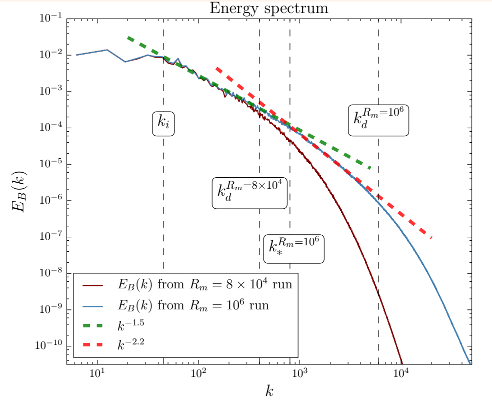


Comisso, et al. ApJ 2018

- Above k_*, current sheet disruption by plasmoid instability is the main cascade mechanism
- Turbulence fluctuations at higher k provide the source of noise for current sheets at lower k

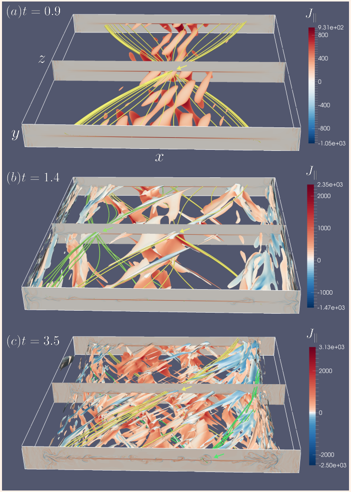
Plasmoids in 2D MHD Turbulence

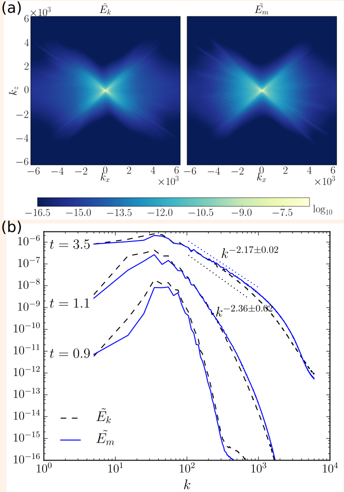




Dong et al. PRL 2018

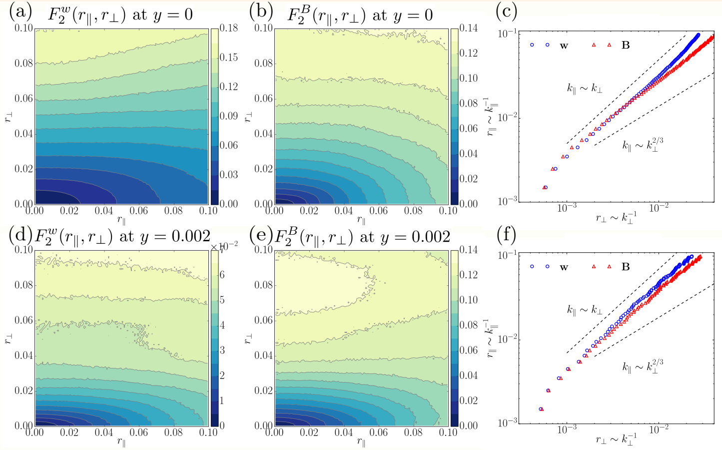
3D Plasmoid Instability $\Longrightarrow$ Self-Generated Turbulent Reconnection





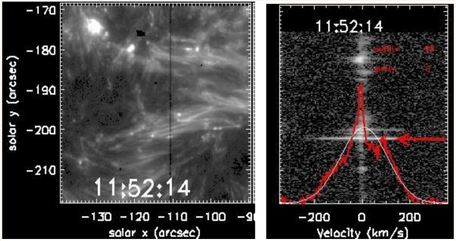
Huang & Bhattacharjee, APJ 2016

Structure Functions in Turbulent Reconnection

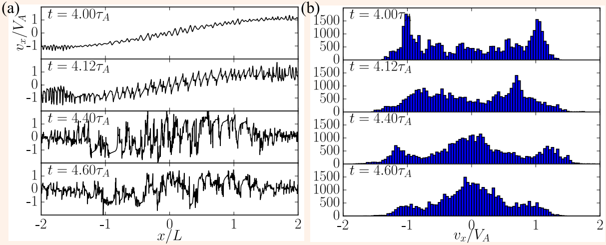


- $k_\perp v_l / k_\parallel V_A \sim O(1) \Longrightarrow$ strongly nonlinear regime
- Eddy anisotropy is nearly scale-independent – as opposed to $k_\parallel \sim k_\perp^{2/3}$ predicted by Goldreich & Sridhar

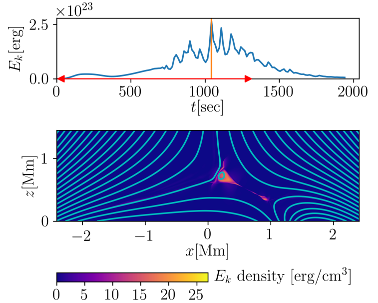
IRIS Observation of UV Burst Event

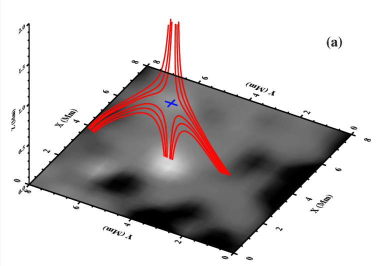


Innes et al. APJ 2015

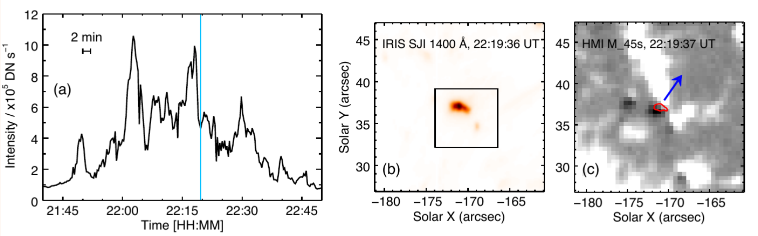


UV Burst Event Driven By Footpoint Motion





Chitta et al. A&A (2017)



Future Perspectives

- The theoretical framework can be applied to models beyond resistive MHD.
- Predictions from theories/simulations may be tested with new experiments, e.g. FLARE.
- Roles of the plasmoid instability in MHD turbulence
  - turbulent reconnection
  - reconnection in turbulence
- High resolution/cadence solar observations